

# **Studies of Ionospheric Irregularities: Origins and Effects**

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## **LONG-TERM GOALS**

We have two long-term goals. The first goal is to understand the electrical properties of the upper atmosphere and space environment to better assist designers and users of space systems and technology. The second goal is to educate the next generation of leaders in space science and engineering.

## **OBJECTIVES**

The scientific objectives of the project are:

- (1) to develop GPS receivers for measuring scintillations and scintillation effects on GPS signals and receivers;
- (2) to investigate the effects of ionospheric scintillation storms on GPS through deployment of GPS scintillation receivers and field campaigns globally at equatorial latitudes, regionally in South America, and at mid-latitudes (Hawaii, Utah, Ithaca, Puerto Rico);
- (3) to assess the threat level of scintillation storms on GPS receivers and help industry develop mitigation strategies;
- (4) to develop GPS receivers that can assess the effect of scintillations on modernized GPS and Galileo signals;
- (5) to develop space-based GPS receivers for sounding rocket and satellite applications.

Our research focuses on the study of waves, irregularities, and wave-particle interactions in space plasmas as well as on the effects of these processes on radio signals and energetic plasmas. Our approach is primarily experimental, and we have a reputation for producing cutting edge instrumentation and developing successful experiments. The vast majority of the universe exists in a plasma state and we focus on our own upper atmosphere and ionosphere as natural laboratories for studying space physics and as an environment that affects satellites and their signals. This yields a mix of applied and curiosity-driven research. By primarily employing sounding rockets and ground-based

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14. ABSTRACT <b>We have two long-term goals. The first goal is to understand the electrical properties of the upper atmosphere and space environment to better assist designers and users of space systems and technology. The second goal is to educate the next generation of leaders in space science and engineering.</b>				
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instrumentation, graduate students are able to participate in the full range of research and develop into future leaders. For example, our development of multiple-sensor plasma wave interferometers, beginning with the Viking spacecraft and continuing with sounding rockets, is now a standard feature of ionospheric and magnetospheric missions. During the past several years we developed a GPS scintillation receiver that has been deployed at multiple sites across South America, Africa, and China. This receiver not only monitors ionospheric scintillation but additionally measures ionospheric drifts. Furthermore, this effort is currently leveraging our development of GPS software receivers and space-based GPS receivers.

## APPROACH

Our scientific strategy emphasizes experimental development. We have chosen this route because the field of space science, especially the electrical properties of space, is still experimentally limited. Theories of space physics and space plasma physics are quite plentiful, but discriminating measurements are few and far between. Within this context one may well ask what areas need the most attention. The answer concerns nonlinear problems involving plasma waves and electric fields in collisionless environments and turbulent media. Incidentally, these areas are also examples that, at one extreme, can test theories of basic plasma physics and, at the other extreme, are important for the development and application of new communication and navigation technologies.

The logistics and operational challenges of ground-based experimentation are relatively new developments in our experimental program since most of our previous work was with space-based experiments. Since we lack the infrastructure to develop our own ground-based measurement program, we have created a new vision or “business plan” for obtaining ground-based measurements. We give GPS receivers away “free” to collaborators who then operate the receivers in regions of geophysical interest and share their data with us. This approach has been highly successful and we have established a regional chain of GPS scintillation receivers in South America (mostly Brazil) from the equatorial anomaly to the geomagnetic equator. Other receivers have been placed in Hawaii, Utah, Ithaca, Puerto Rico, Eritria, and China. We are also extending our expertise in ground-based receivers to space flight. Three receivers were launched in a sounding rocket investigation of the northern lights and we are working with a colleague (Dr. Mark Campbell) to create a GPS receiver for a CUBEsat project. This latter instrument will be used to sense ionospheric scintillations of GPS signals in orbit for the first time.

## WORK COMPLETED

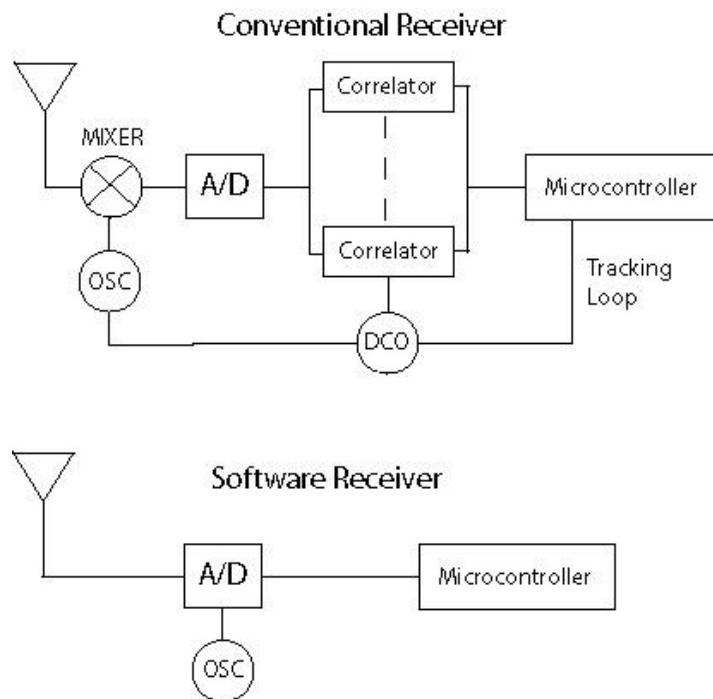
- (1) Invented the first 12-channel GPS software receiver, applied for a patent, and are discussing applications with industrial partners.
- (2) Analyzed GPS equatorial scintillation data from a three-month campaign, employing five receivers on a 700 m by 1000 m grid, and demonstrated the speed, shape, and duration of fades.
- (3) Developed a Linux-based GPS scintillation receiver that operates over the web in real time. See, for example, <http://gps.ece.cornell.edu/>, where nightly scintillations in Brazil, Hawaii, Utah, Puerto Rico, and NY can be observed.
- (4) Developed, fabricated and flew three sounding rocket “class” GPS receivers in an auroral sounding rocket experiment involving multiple payloads.
- (5) Conducted a three-month joint radar-GPS receiver campaign at Sao Luis, Brazil on the magnetic equator to determine the altitude of the irregularities producing GPS scintillations.

- (6) Demonstrated an orbital GPS scintillation receiver concept for CUBEsat.
- (7) Created a GPS scintillation test pattern for use with GPS signal simulators.

## RESULTS

From item (1): We have created the first 12-channel GPS software receiver. The prototype runs on a 1.4 GHz Pentium 4 using an aliasing down converter. The software receiver replaces all of the special purpose correlation hardware with software. Figure 1 illustrates the difference between a conventional hardware receiver and a software receiver. A software receiver has several advantages over a hardware receiver. First, it can be updated easily, which is important for the next decade when GNSS signals will be changing rapidly with modernized GPS and Galileo.

Second, it can share processor resources with other device functions. For example, a digital camera using a signal processing chip could share the chip with the GPS software receiver to time and location-stamp the images. We are discussing exactly this application with an industrial partner. The software receiver uses a unique approach and we have applied for a patent.



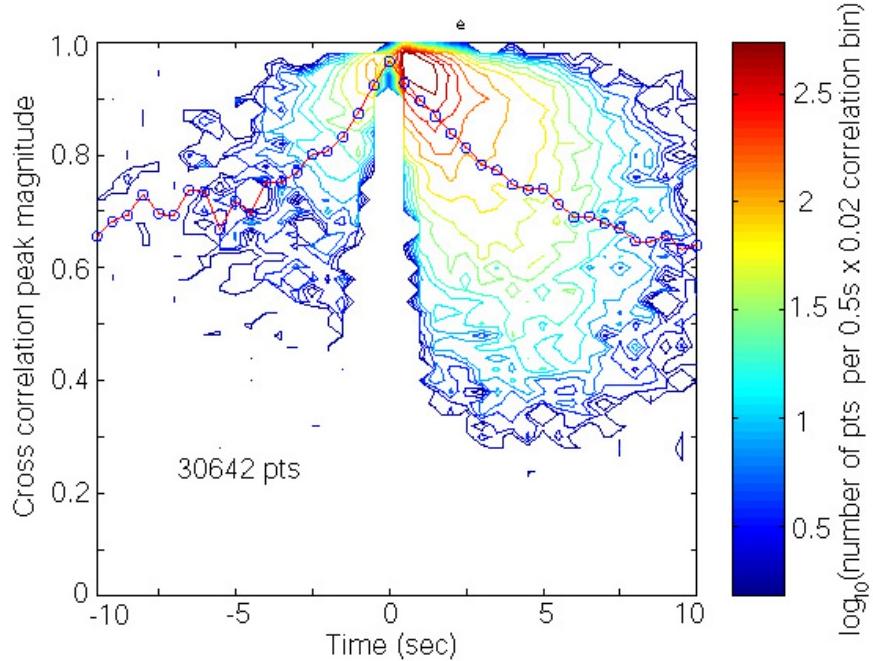
**Figure 1: A schematic diagram of a conventional hardware receiver and a software receiver. The software receiver is much less complex.**

From item (2): In the previous report year we conducted a special three-month campaign in Cachoeira Paulista, Brazil, under the equatorial anomaly, to understand and parameterize the spatial and temporal characteristics of GPS L1 scintillations. This campaign produced 100 GB of data, which have been transferred to hard disk drives for analysis. The resulting data have been reduced to cross-correlation coefficients among the five receivers, which are amenable to analysis. From the cross-correlation data, we have investigated the spatial and temporal properties of amplitude fades. Note that this is a different approach from most research that has typically investigated scintillation climatology through

the S4 index. That is, others have addressed the questions of when, where, and how much. On the other hand, we have investigated the questions of how fast, what shape, and for how long because these questions are important in understanding the potential effect of scintillation on moving GPS receivers.

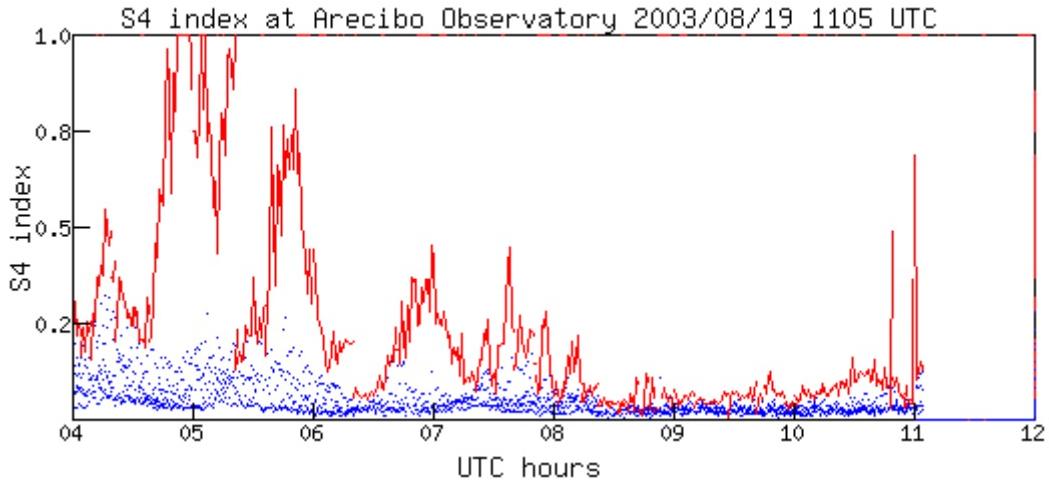
Scintillations or fades can be thought of as a translating spatial pattern that is evolving in its own reference frame. Hence fades may appear to be quite different in the reference frame of a moving receiver. The most important aspect of this viewpoint is the fading time scale for a receiver moving with the velocity as the fade pattern.

We determined fade time scales that resonant GPS receivers would observe. Figure 2 shows the decay of the cross-correlation magnitude with time for both eastward (positive) and westward (negative) velocities. After 10 seconds one would expect a significant fraction of the fades to have a cross-correlation magnitude of greater than 0.8, implying that they are essentially unchanged. We conclude from Figure 1 that the time scale for significant fade amplitude decay is about 10 s.



**Figure 2. The distribution of cross-correlation amplitudes as a function of time in the resonant reference frame. The distribution is created with 30642 cross-correlations of 40 and shows the cross-correlation amplitude decreasing with time but still significantly large after 10 s.**

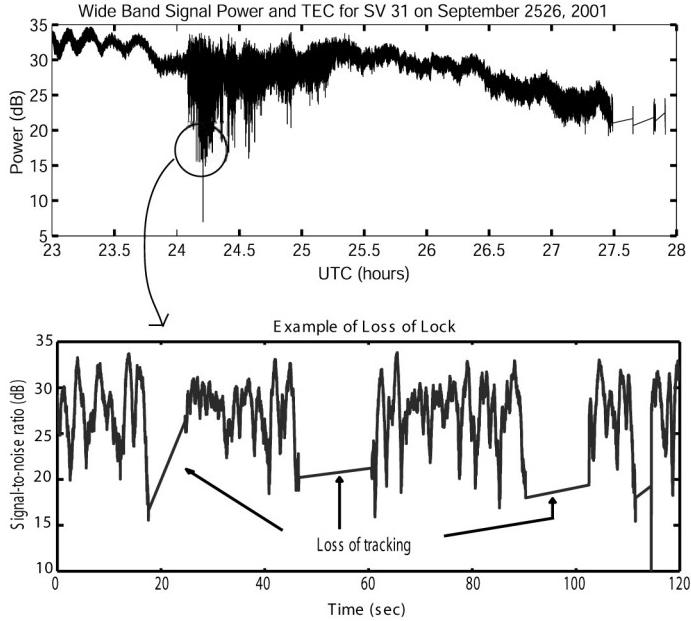
From item (3): We are developing remotely operating GPS scintillation receivers that are accessible over the web. All of the sites may be found at <http://gps.ece.cornell.edu/> under the real-time data button. In addition to equatorial sites, we are accumulating scintillation data for the first time at mid-latitudes. Figure 4 demonstrates an example of scintillations at Puerto Rico. The S4 index has large values frequently exceeding 0.8 and occasionally 1. Since this latitude maps to above the spread-F equatorial ionosphere, it is a mid-latitude station and not expected to exhibit the large values of S4 seen in Figure 3.



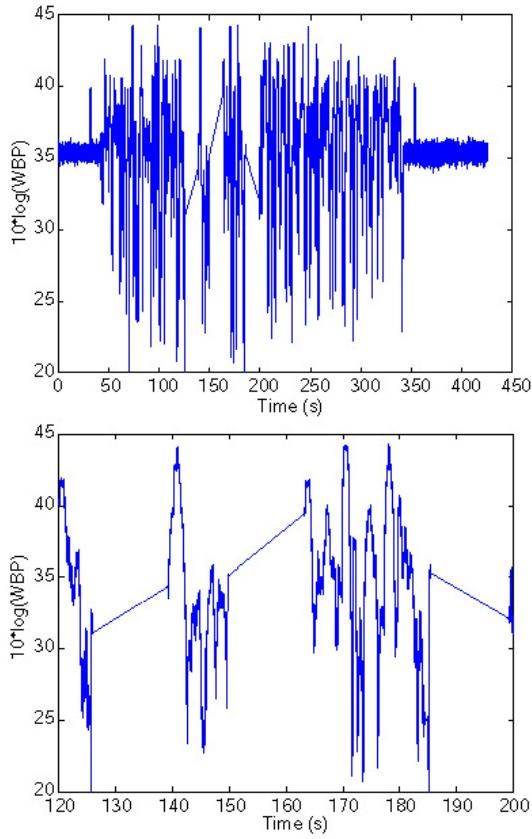
**Figure 3.** An example of S4 index data showing scintillations at Puerto Rico. This is an example of a real-time plot available on the web and shows that GPS scintillations can be severe at this latitude.

A similar receiver operating in Ithaca, NY observed GPS scintillations adequate to cause loss of lock. Figure 3 shows an example of these fades, which occurred during a modest magnetic storm on September 25-26, 2001 [Ledvina et al., 2002]. In this example a large ionospheric density surge, sometimes called a storm-enhanced density event, moved up the east coast of the U.S., encountering the subauroral ion trough. The encounter resulted in steep density gradients (not shown) and large amplitude scintillations, large enough to produce the loss of tracking shown in Figure 4.

From item 7 we created a scintillation test pattern using measured data from the equatorial anomalies. This test pattern consists of 5 minutes of steady, moderate amplitude scintillations from a high elevation satellite. The advantage of the test pattern is that it can be scaled in amplitude and time for GPS signal simulators to test GPS receivers. The test pattern has been submitted for publication in the new AGU publication, *Space Weather*, and is proposed as a standard for evaluating GPS receiver performance. Figure 5 shows an example of a GPS receiver response to the test pattern and accompanying loss of lock. The upper panel shows the received signal wide-band amplitude for the 300 s-long test pattern and the lower panel shows an expanded view of the period during which loss of tracking occurred.



**Figure 4.** An example of GPS scintillations occurring at mid-latitudes (Ithaca, NY). The amplitude scintillations occurred during a minor magnetic storm ( $D_{st}=100$  nt) and began at about 2400 UTC. The S4 index was nearly one and resulted in loss of tracking on several satellites. An example of loss of tracking is shown in the lower panel.



**Figure 5.** Received GPS signal amplitudes from a simulator programmed with a scintillation test pattern. The receiver fails to track for several 15 s periods during the simulated scintillations.

## **IMPACT/APPLICATIONS**

Our work with GPS receivers and measurement of scintillations continues to be important in understanding and predicting the behavior of GPS receivers in the presence of scintillations. Determining the shape of fade patterns is important to understanding how velocity resonance will occur and potentially produce loss of lock or even loss of navigation in GPS receivers. The recent work on time scales is critical for determining the potential for airborne GPS receivers to have added sensitivity to GPS scintillations.

The expansion of our GPS scintillation program to mid-latitudes has been very fruitful. Not only have we been able to show that field lines mapping to well above the equatorial ionosphere produce spread-F disturbances in Hawaii, but we have also demonstrated that substantial ( $S4=1$ ) scintillations can occur in the northern United States.

## **TRANSITIONS**

The transitions in our program are required by the transitions in GNSS, GPS, and Galileo. Starting with our current receivers, both hardware and software, we will develop new receivers for measuring scintillations on the WAAS signal, the new L2 civilian code, and Galileo signals. We will continue to expand our global chain of receivers with colleagues by offering them free GPS technology in return for GPS receiver operation. Finally, we will explore quantitatively the morphology of GPS scintillation storms to characterize the occurrence of severe scintillation disturbances.

## **RELATED PROJECTS**

Our NASA projects depend heavily on the funding of GPS receiver development. For example, the results from the ground-based GPS scintillation receivers were critical in determining goals for the LWS/Geospace Mission Definition Team report. The sounding rocket program at Cornell uses GPS receivers originally based on the scintillation receiver design.

The CUBEsat program, with which we are collaborating, uses a receiver based on the Cornell sounding rocket design and the GPS signal simulator, purchased with DURIP funding, is being used to develop and test the CUBEsat GPS receiver. In return we hope to make the first ever GPS amplitude scintillation measurements from orbit using the CUBEsat receiver.

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